UNIVERSITY OF Cincinnati

Aggregation of Heterogeneous Units in a Swarm of Robotic Agents

Manish Kumar
University of Cincinnati,
Cincinnati, OH

Devendra P. Garg
Duke University,
Durham, NC

4th International Symposium on Resilient Control Systems
Aug. 10, 2011
Boise, Idaho

CDS
Cooperative Distributed Systems Lab

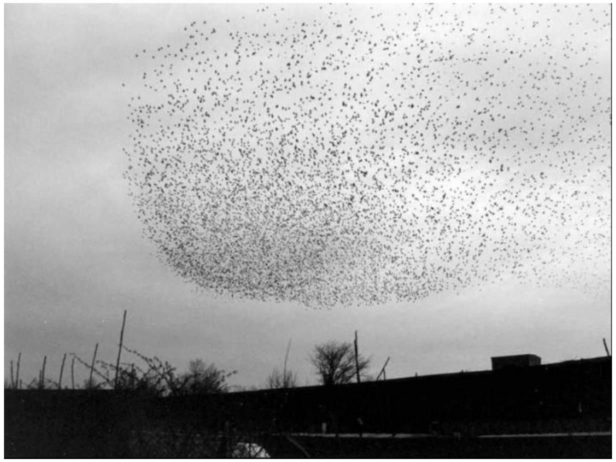
Outline

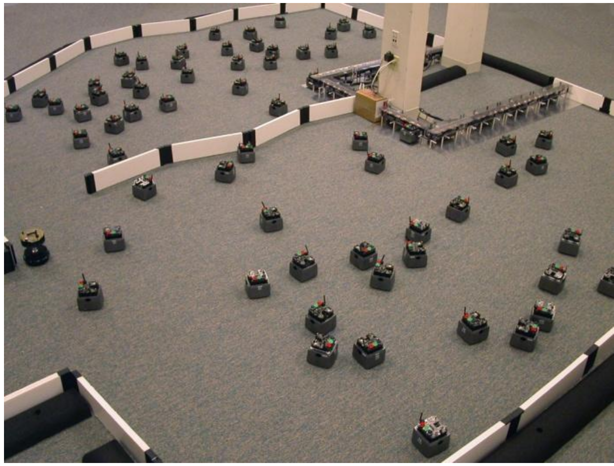
- Introduction
  - Motivations and applications
  - Swarm robot control methodologies
  - Problem formulation
- Examples from Biology
- Control Law Development
  - Differential potential function
- Analysis of System Under Applied Control Law
  - Stability of system
- Simulation Results and Discussion
- Conclusions

Swarm Intelligence

- Swarm Intelligence is the property of a system consisting of several entities or agents whereby the ***individual behaviors*** of simple agents ***interacting locally*** with their environment and amongst themselves cause ***coherent functional global patterns*** to **emerge**.
- Swarm Intelligence provides a framework for solving complex problems in a distributed manner ***without centralized control*** or the need of a ***global model***.

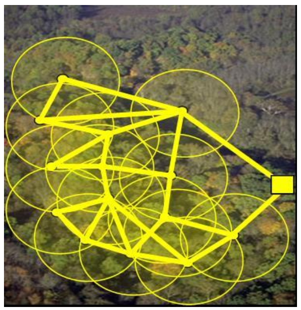
Swarm Intelligence



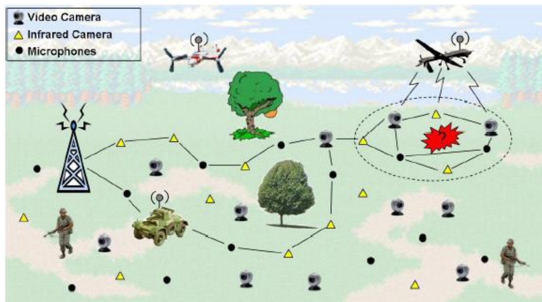


Applications

Mobile sensor networks



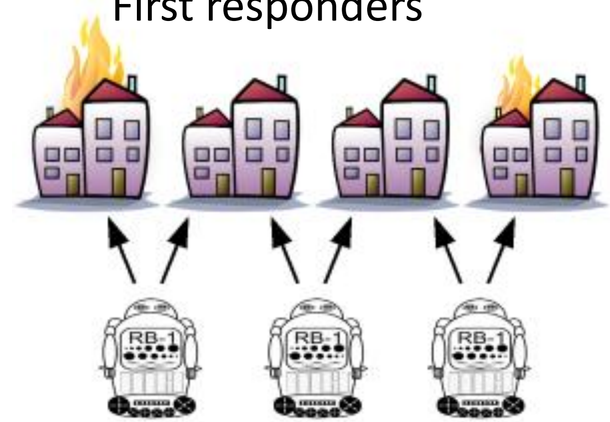
http://am0nr4.blogspot.com/2010_04_01_archive.html



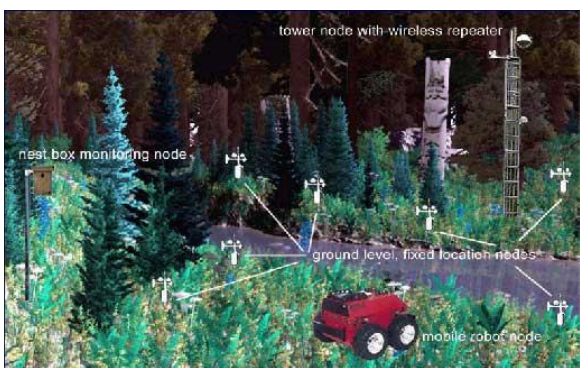
http://www2.ece.ohio-state.edu/~ekici/res_wmsn.html

Natural disasters

First responders

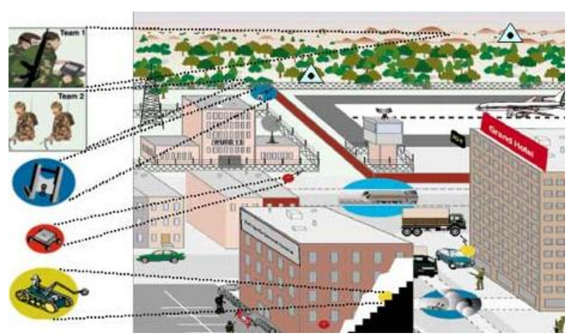


http://decpucs.isr.ist.utl.pt/



Environmental monitoring

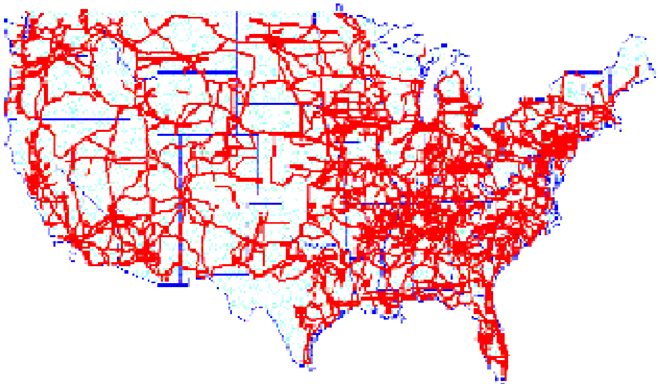
Source: www.cs.ucla.edu/~jessicaf/



Source: http://www.darpa.mil/ato/programs/tmr.htm

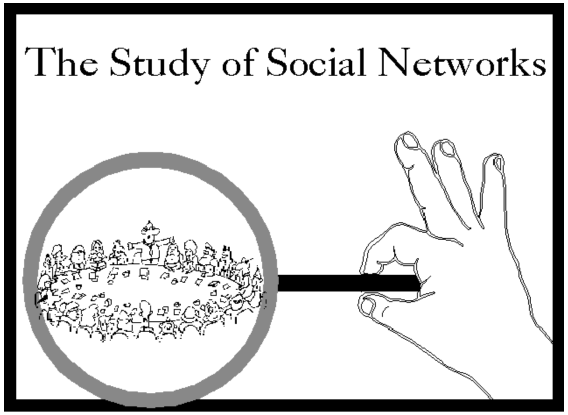
Military surveillance

Complex Networked Systems: Examples



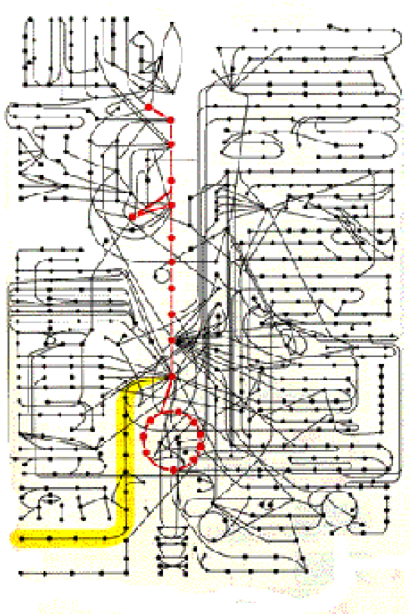
National Electric Power Grid

Source: http://www.anl.gov/Media_Center/logos22-1/electricity.htm



Social Network

http://www.insna.org/images/



Metabolic Network

Alberts A, Bray D, Lewis J, Raff M, Roberts K, Watson JD (1994) Molecular Biology of the Cell, p83, Garland, New York.]

School of Fish

www.uscg.mil/d14/units/KUKUI/Midway%202003.htm

Swarm Robot Control Methodologies

- Behavior Based Techniques[1]
  - Each agent has a defined set of behaviors
- Rigid Graph Theory[2]
  - Distance between neighboring agents maintained
- Leader-Follower[3]
  - Agents follow their leader
- Artificial Potential Function[4,5]
  - Interaction between neighboring agents captured via artificial potential functions

1. Balch and Arkin, 2003

2. Olfati-Saber and Murray, 2002

3. Tanner, Pappas, and Kumar, 2004

4. Leonard and Fiorelli, 2001

5. Olfati-Saber, 2006

Swarm Robot Control

- Three attributes of swarm robot control algorithms
  - Decentralization, anonymity and modularity*
- Artificial potential function based approach provides a mechanism to achieve the above

*Michael et al, *IEEE Robot. and Auto. Mag.*, 2008

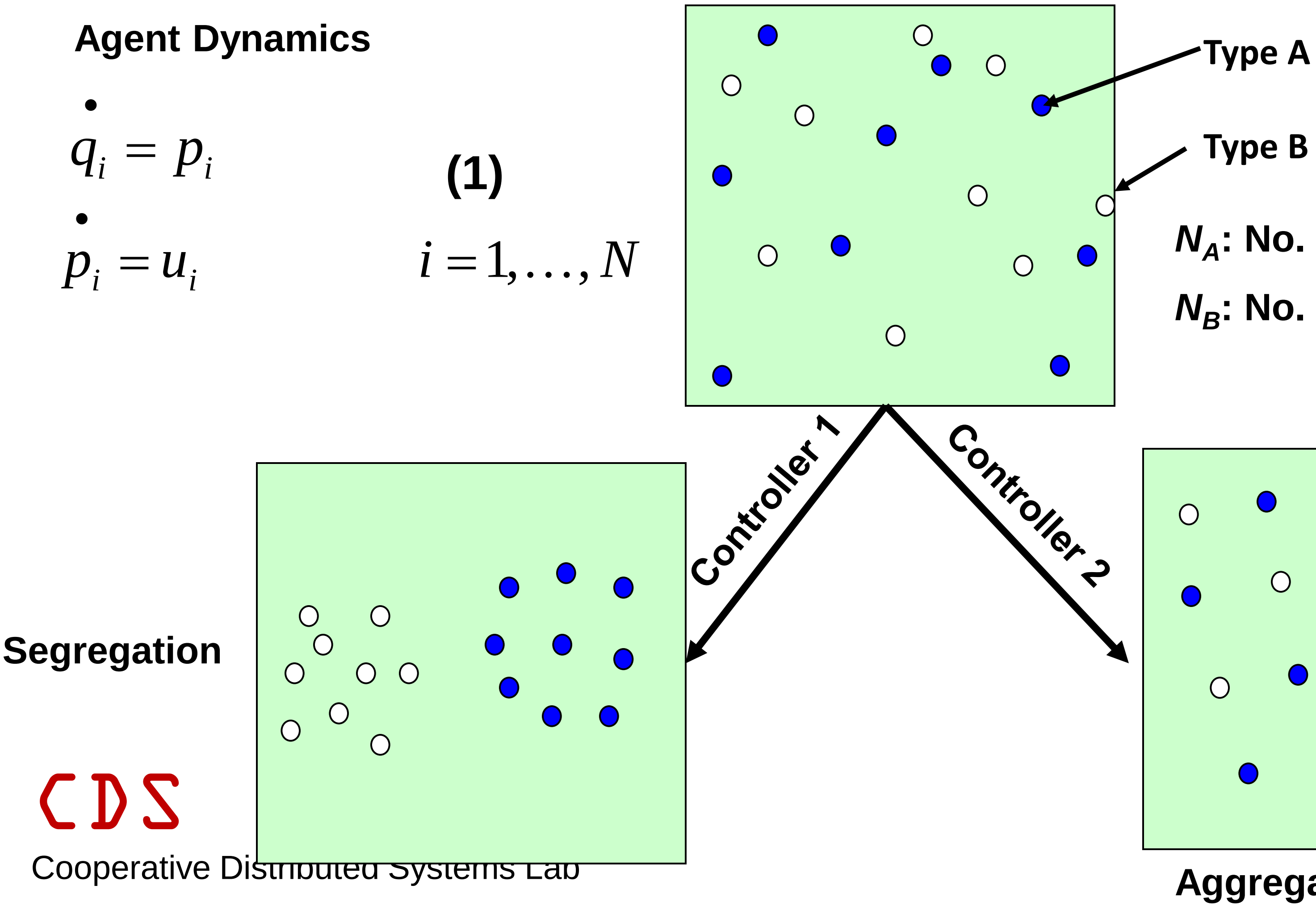
Aggregation / Segregation Example

– Problem Formulation: Heterogeneous Robots

Agent Dynamics

$$\dot{q}_i = p_i$$

$$\dot{p}_i = u_i \qquad \textbf{(1)} \qquad i = 1, \ldots, N$$



N_A: No. of Agents of Type A

N_B: No. of Agents of Type B

Conditions for Segregation and Aggregation

Segregation: $r_{avg}^{AA} < r_{avg}^{AB}$ $\quad r_{avg}^{BB} < r_{avg}^{AB}$

Aggregation:

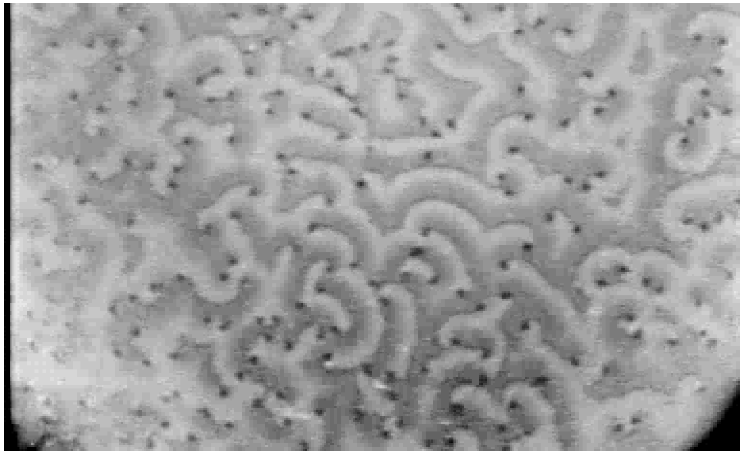
Metric 1 $r_{avg}^{AA} > r_{avg}^{AB}$ $\quad r_{avg}^{BB} > r_{avg}^{AB}$

Metric 2 $r_{avg(NN)}^{AA} > r_{avg(NN)}^{AB}$ $\quad r_{avg(NN)}^{BB} > r_{avg(NN)}^{AB}$

Biological Examples of Sorting, Aggregation, and Segregation

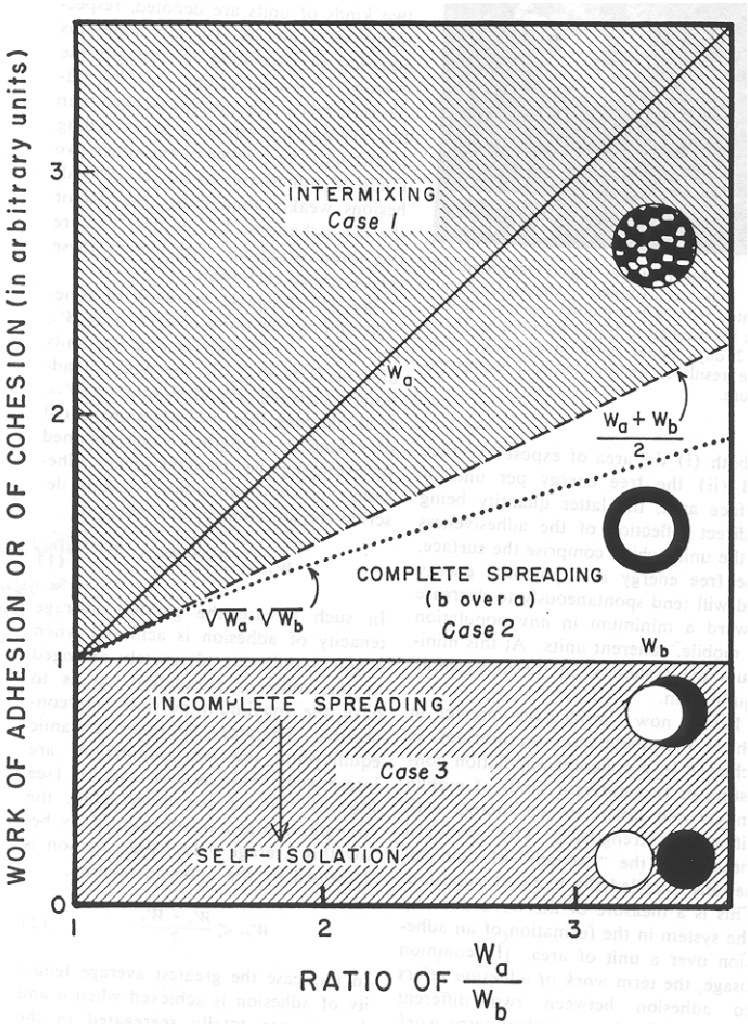
- Brood Sorting in Ants
- Cemetery Organization
- Aggregation/Segregation Behavior in Cockroaches
- Association/Dissociation of Cells
- Morphogenesis

www.scottcamazine.com/.../pages/antBrood_jpg.htm



http://dictybase.org/Multimedia/morphogenesis

Example Association/Dissociation of Cells



Steinberg, Science, 1963

$$W_{ab} \geq \frac{W_a + W_b}{2}$$

$$\frac{W_a + W_b}{2} > W_{ab} \geq W_b$$

$$W_a \geq W_b > W_{ab}$$

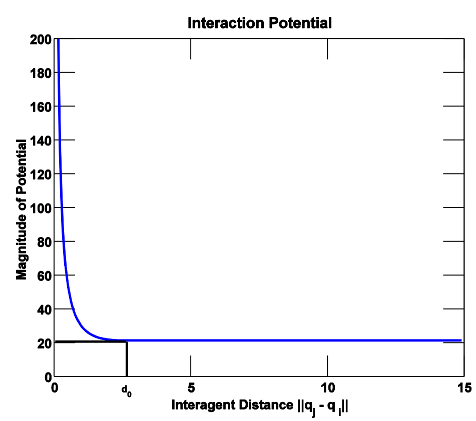
Control Law

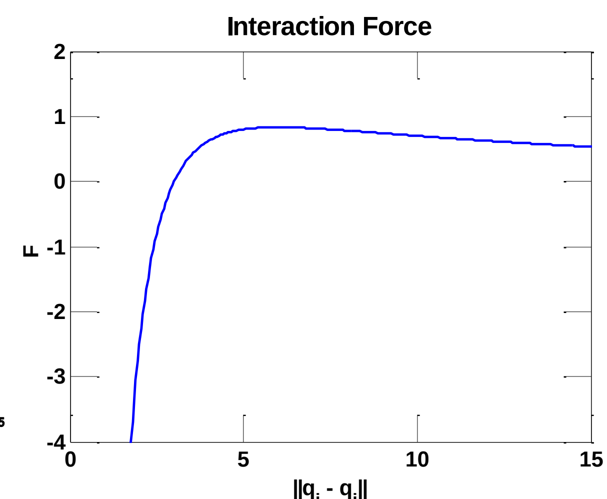
Distributed Control Action

$$u_i = \underbrace{-\sum_{j \in N_i} \nabla_{q_i} V_{ij}(\|q_j - q_i\|)}_{\text{Gradient of Artificial Potential Function}} \underbrace{- a \sum_{j \in N_i} (p_i - p_j)}_{\text{Term Representing Damping}} \qquad (2)$$

Interaction Potential

$$V_{ij} = a\left(ln(q_{ij}) + \frac{d_0}{q_{ij}} \right)$$





CDS
Cooperative Distributed Systems Lab

Leonard & Fiorelli, *Conf. on Decision and Control*, 2001

Control Law

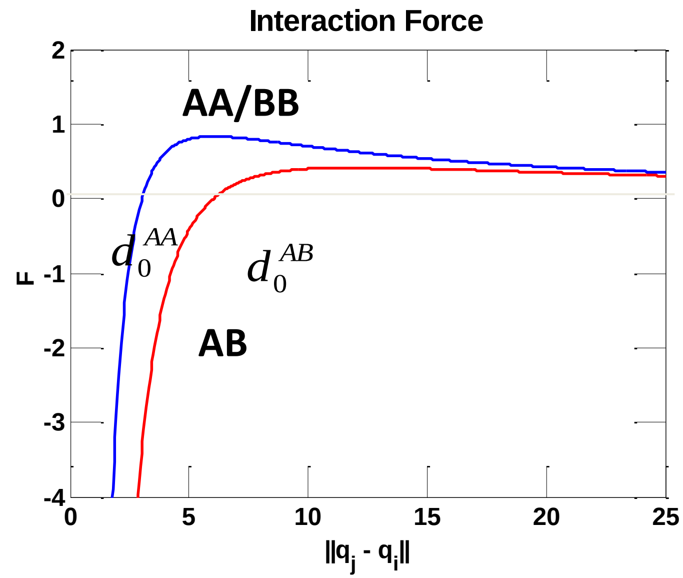
Differential Potential

A-A Interaction:

$$V_{ij}^{AA} = a\left(ln(q_{ij}) + \frac{d_0^{AA}}{q_{ij}}\right)$$

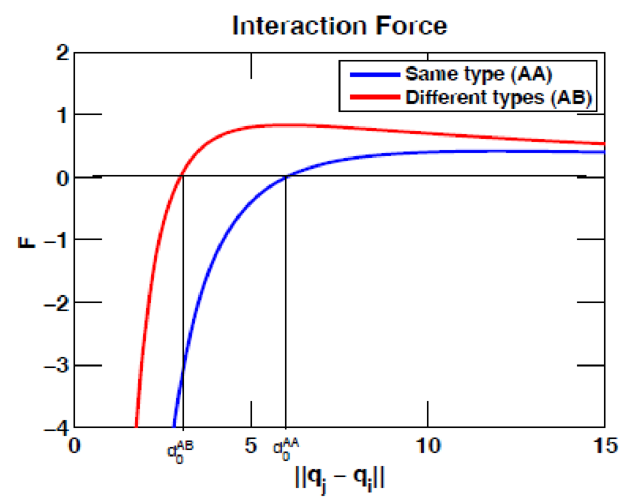
A-B Interaction:

$$V_{ij}^{AB} = a\left(ln(q_{ij}) + \frac{d_0^{AB}}{q_{ij}}\right)$$



Condition for Segregation $d_0^{AA} = d_0^{BB} < d_0^{AB}$

Condition for Aggregation $d_0^{AA} = d_0^{BB} > d_0^{AB}$



Controller Analysis

Analysis of Convergence and Stability Properties

Lemma: Consider a system of *N* mobile agents. Each agent follows the dynamics given by Equation (1), and with feedback control law given by Equation (2). For any initial condition belonging to the level set of $\phi(q,p)$ given by $\Omega_C = \{(q,p) : \phi(q,p) \le C\}$ with C>0, and when the underlying graph of the system is connected all the time, then the system asymptotically converges to the largest invariant set in $\Omega_I \subset \Omega_C$. The points in largest invariant set Ω_I are bounded, the velocity of all agents match and the total potential of the system approaches a local minimum.

Proposition (Segregation)

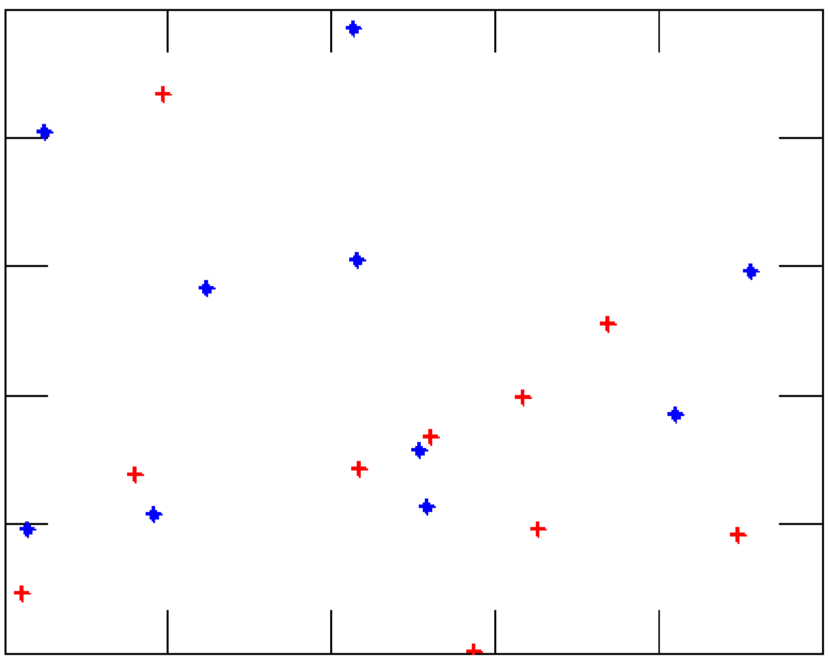
A system of heterogeneous swarming agents consisting of two types of agents and following dynamics given by Equation (1) and control law given by Equation (2) flock together such that the average distance between the agents of different types r_{avg}^{AB} is bounded from below by the parameter d_0^{AB}.

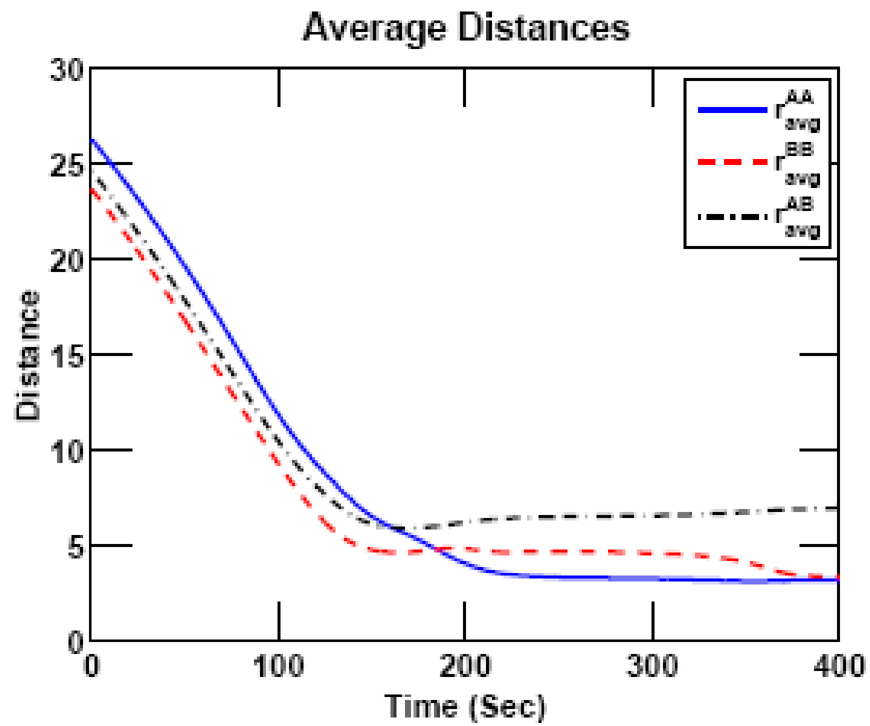
M. Kumar et al., *IEEE Trans. Automatic Control,* 2010

Simulation Studies

N_A = 10, N_B = 10

$$d_0^{AA} = d_0^{BB} = 3 \quad d_0^{AB} = 6$$





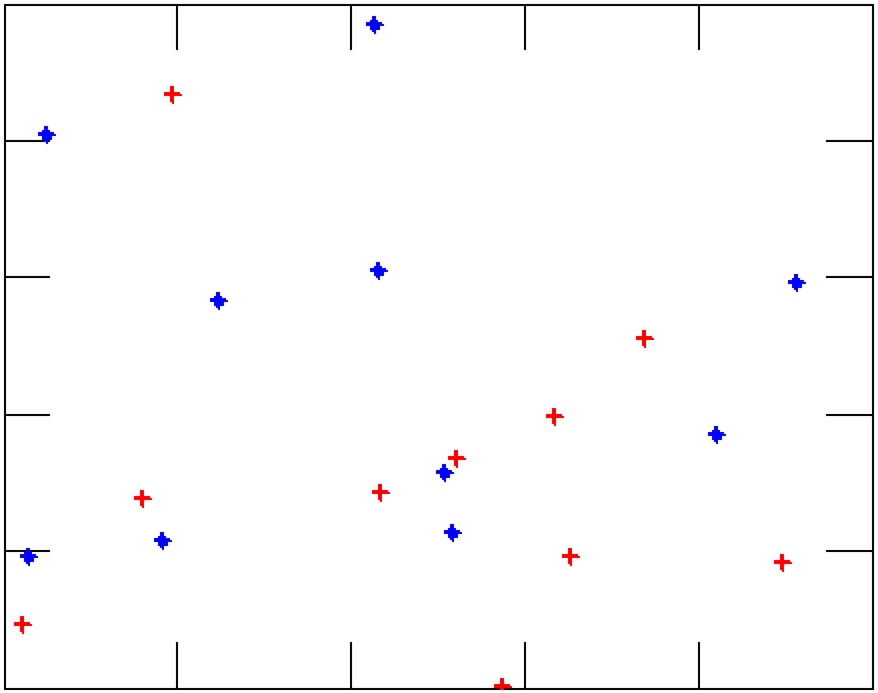
Cooperative Distributed Systems Lab

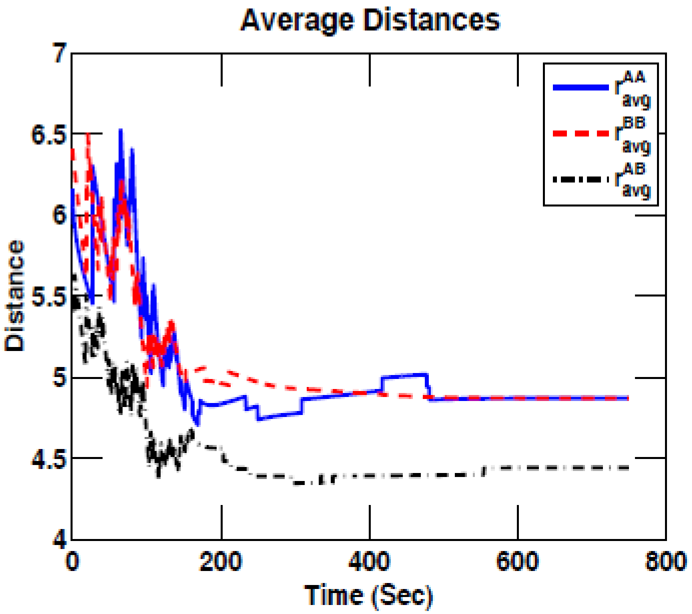
Segregation

Simulation Studies

N_A = 10, N_B = 10

$$d_0^{AA} = d_0^{BB} = 6 \quad d_0^{AB} = 3$$





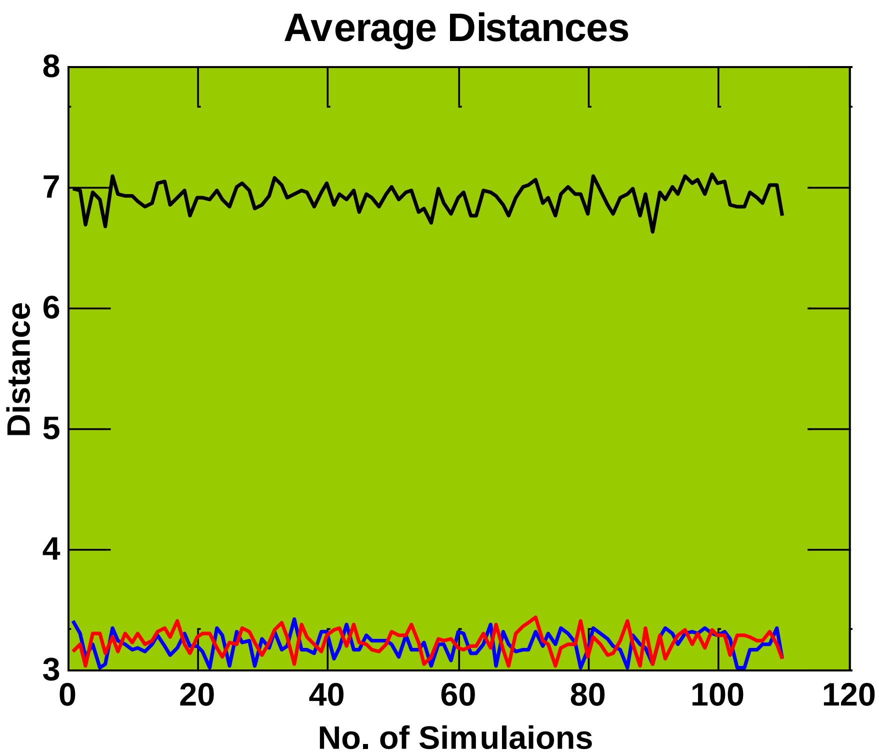
Aggregation

Cooperative Distributed Systems Lab

Simulation Studies

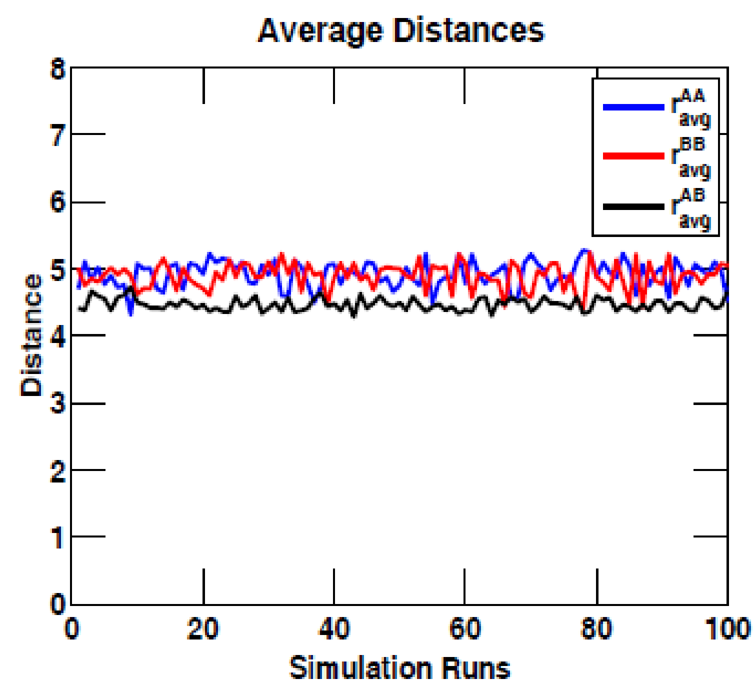
Simulation was carried for more than 100 times. N_A , N_B varying randomly between 5 and 20

$$d_0^{AA} = d_0^{BB} = 3 \quad d_0^{AB} = 6$$



Segregation

$$d_0^{AA} = d_0^{BB} = 6 \quad d_0^{AB} = 3$$

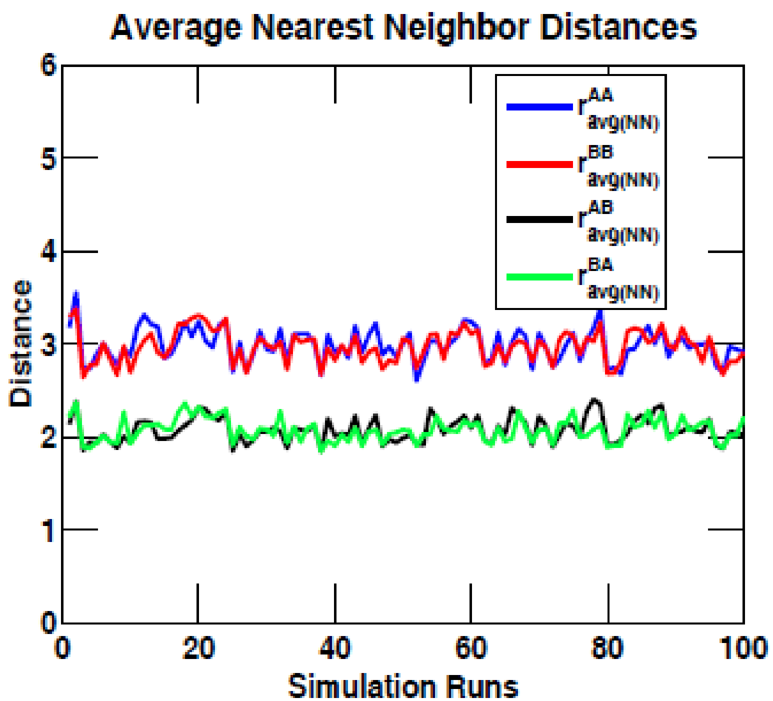


Aggregation

Simulation Studies

Simulation was carried for more than 100 times. N_A , N_B varying randomly between 5 and 20

$$d_0^{AA} = d_0^{BB} = 6 \qquad d_0^{AB} = 3$$



Aggregation

Conclusions: Segregation/Aggregation Behavior in Swarm of Heterogeneous Robots

– **Innovative Control Laws Introduced Based on Differential Potential**

– **Extensive Simulation Studies Verify the Effectiveness of the Proposed Approach**

– **Analysis of Control Laws Explains the Behavior which is also Seen in Natural Systems**